COMPUTATIONAL TECHNIQUES TO ASSESS THE EFFECTS OF IONIZATION ON HIGH POWER ELECTRICAL SYSTEMS

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Abstract

There are three general classes of codes that can be used in the analysis of electrical systems and their interactive effects: circuit codes, Maxwell's-equations-solving codes (also referred to as field codes), and system codes. Circuit codes employ coupled equations to describe the currents and voltages associated with individual electronic components such as individual transistors, resistors, and capacitors. The largest group of codes is the Maxwell's-equation-solving codes. Conceptually, these codes can be subdivided into frequency- or time-domain codes and statistical codes. There is an additional way of differentiating between the two major categories of Maxwell's-equations-solving codes available for analyses in this area: those that cannot handle discrete particles or macro-particles, and those that can. These two major categories of codes are referred to as linear and nonlinear (self-consistent), since nonlinear effects such as volume or surface breakdown often require a self-consistent analysis. Finally, system codes are used to understand and study the relationship between various elements in a high-power system: sources, transmission lines, antennas, propagation effects, etc. System codes consider the constraints on an electrical system, such as size, weight, and power, and are used to define what components may be used to deliver the required results. The element that most frequently limits a given code's capability to adequately model a system lies in understanding and depicting electron-interaction phenomena with other particles, gas breakdown and streamer formation, and the effects of photo ionization. This paper is based on a study carried out by the Air Force Research Laboratory in 2003 to review the available codes and determine their capability to assess the effects of ionization on advanced high power electrical systems [1].

I. INTRODUCTION

The three general classes of codes that may be used in the analysis of electrical systems and their interactive effects are circuit codes, Maxwell's-equations-solving codes (field codes), and system codes.

The largest group of codes is the Maxwell's equation solving codes. These can be subdivided into frequency- or time-domain codes and statistical codes. The capabilities required to model high-power, electromagnetic processes include the ability to solve Maxwell's equations, to track groups of charged particles, and to model the chemistry of solids, gases, and liquids. Chemistry is the term used in this paper to describe the formation of ions, neutrals, and free electrons in a material. Typically, codes are developed to model these phenomena for a specific problem. Thus, they are applicable over different ranges of field magnitudes, plasma and material densities, temperatures, thermodynamic equilibrium, and time regimes. There does not exist a single universal code to attack all problems. Therefore, the system under study must be defined to a certain extent before an analysis can begin.

There is a subdivision or second conceptual difference creating two major categories of Maxwell's-equations-solving codes available for analyses in this area: those that can handle discrete particles or macro-particles, and those that cannot. The effect of this difference is the degree of self-consistency attained in the solution. If the driving currents and conductivities are defined throughout the computational volume, Maxwell's equations can be simply solved without self-consistency. If however, the fields generated affect the driving current and the conductivity, then a self-consistent approach is necessary. The self-consistency is attained through treating the driving current as discrete particles with their trajectories modified by the resulting fields. Similarly, if secondary electrons (created through interactions between the driving currents or the electric fields and a material) can move distances more than a fraction of a wavelength, they

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14. ABSTRACT
There are three general classes of codes that can be used in the analysis of electrical systems and their interactive effects: circuit codes, Maxwells-equationssolving codes (also referred to as field codes), and system codes. Circuit codes employ coupled equations to describe the currents and voltages associated with individual electronic components such as individual transistors, resistors, and capacitors. The largest group of codes is the Maxwells-equation-solving codes. Conceptually, these codes can be subdivided into frequency- or time-domain codes and statistical codes. There is an additional way of differentiating between the two major categories of Maxwells-equations-solving codes available for analyses in this area: those that cannot handle discrete particles or macro-particles, and those that can. These two major categories of codes are referred to as linear and nonlinear (self-consistent), since nonlinear effects such as volume or surface breakdown often require a self-consistent analysis. Finally, system codes are used to understand and study the relationship between various elements in a high-power system: sources, transmission lines, antennas, propagation effects, etc. System codes consider the constraints on an electrical system, such as size, weight, and power, and are used to define what components may be used to deliver the required results. The element that most frequently limits a given codes capability to adequately model a system lies in understanding and depicting electron-interaction phenomena with other particles, gas breakdown and streamer formation, and the effects of photo ionization. This paper is based on a study carried out by the Air Force Research Laboratory in 2003 to review the available codes and determine their capability to assess the effects of ionization on advanced high power electrical systems [1].

15. SUBJECT TERMS

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must be tracked as discrete particles. This tracking can employ particle pushing or fluid approaches. These two major categories of codes will be referred to as linear (not self-consistent) and nonlinear (self-consistent) since nonlinear effects such as volume or surface breakdown often require a self-consistent analysis.

There is one common weakness among the nonlinear codes. There does not exist an adequate description of interactions between electrons, ions, neutral particles, and possibly, ultra-violet radiation. This weakness is shown by the relatively simple approaches in typical use for the material chemistries and the initiation of breakdown in a vacuum or a dielectric. Material breakdown is still a subject of active research with many unproven hypotheses and few experimental comparisons between data and theory. Data for electron cross sections are also under investigation, but it is mainly a matter of obtaining enough experimental data to describe the cross sections between the electrons and the other species in the volume. These relate to the probabilities of certain collision based particle-particle interactions occurring in the media. Electron cross sections are used to describe the formation of ions in the plasma as a function of the materials and fields present. To date, there are many types of materials, densities, and fields where these cross sections are unknown. Fortunately, data and models are available for most of the common, high-power scenarios.

Linear codes and computational speeds have reached a degree of sophistication that very complex problems (i.e., those with many details of conductors, their placement, and the properties of dielectrics) can be solved. If the detail necessary is available for these codes, it is just a matter of time for the modeler to arrive at an answer. These answers include: radar cross sections, antenna patterns, cavity structures, and system responses. However, many times these details are not known, and a statistical type of code may be usefully employed. For a given time and location, these codes may give a less precise answer than the deterministic codes, but they can generate the behavioral statistics of the solution with much smaller resources than the codes yielding the exact solution. These typically give the probability that a condition or response of interest may or may not occur. Two areas of coupling to systems are poorly handled at present: aperture and cavity effects. Although both are well understood analytically, the level of detail needed for the calculations is not. If all details of the construction and conductor placement are known, three-dimensional codes can evaluate an answer. However, these details are rarely known, even in equipment supplied with construction drawings. At this time, a statistical approach is best for the coupling analysis of poorly defined systems.

II. DESCRIPTION OF THE PROBLEM

When approaching the analysis of a circuit, the operational characteristics of the circuit must first be known or defined. Typical characteristics may be generic such as a driven integrated circuit, a power source, the transmission line to a radiator, the radiator itself, a platform or target, or components of these elements. The principal characteristics that force the use of different codes are materials and field strengths. Other characteristics may describe a range in plasma densities, types of dielectrics, time scales, material densities, vacuum, field strengths, etc. The characteristic parameters of a circuit can then reveal the problem for analysis and determine what codes should be used. The parameters can indicate the following:

- If the code needs to solve the interaction of transistors and other circuit components.
- If the code needs to solve the interaction of a radiated field with the platform or target.
- If the code needs to follow individual groups of particles (as opposed to local changes).
- If insulator or surface breakdown is expected.
- If material chemistries are important over a range of densities and temperatures.

III. APPLICABLE CODES

A. Circuit Codes

Circuit codes employ coupled equations to describe the currents and voltages associated with individual electronic components such as individual transistors, resistors, and capacitors. These typically are used to show the performance of an electronics package, but they may also be used to describe the effects of ionization or other disruptive influences on the behavior of the electronics package as a unit.

SPICE [2] and SCEPTRE [3] are examples of general-purpose circuit simulation programs for nonlinear dc, nonlinear transient, and linear ac analyses. Circuits may contain resistors, capacitors, inductors, mutual inductors, independent voltage and current sources, four types of dependent sources, lossless and lossy transmission lines (two separate implementations), switches, uniform distributed RC lines, and the five most common semiconductor devices (diodes, bipolar junction transistor (BJTs), JFETs, metal-semiconductor field effect transistor, MESFETs and MOSFETs). A large number of models (many thousands) of circuit components have been created for use in SPICE. SPICE was originally developed at the University of California at Berkeley and has been extensively modified in the private sector.

B. Field Codes

1) Linear/Non-Self-Consistent Maxwell's Equations Solving Codes

Straight Maxwell's equations solvers can find the fields within cavities, power-transmission segments, radiating from antennas, and incident on platforms or targets as long as the problem is linear (no material breakdown) or self-consistency between sources and fields is not required. The most common variety of linear codes is the three-dimensional finite difference time domain (FDTD) codes; examples of these are TSAR [4] and THREDE [5]. Other general-purpose tools for linear electromagnetic effects are contained in the POISSON/SUPERFISH [6] suite of codes developed by Los Alamos. POISSON and SUPERFISH are the primary elements in a collection of codes for calculating static and dynamic electric and magnetic fields in two-dimensional Cartesian or axially symmetric cylindrical coordinates. These codes are typically used to develop accelerator geometries, Marx banks, switches, transmission lines, and vacuum insulator stacks. A final type of linear solution to Maxwell's equations is embodied in STEM [7]. STEM is applicable to the description of extremely complex systems, such as the interiors of aircraft equipment bays, satellites, and other enclosed volumes with a large number of conductors and scatterers present.

2) Nonlinear/Self-Consistent Maxwell's Equations Solving Code

Codes used in the description of source particles, breakdown regions, or areas of ionization that require self-consistency are typically particle-in-cell (PIC) codes. These have the capability to model the movement of charged source particles, the creation of charge separation, the ionizing effects of the electrons and ions, and the self-consistent movement of all charge through the volume. PIC codes group the individual charged particles into macroparticles and follow these rather than attempting to monitor extremely large numbers of particles. Typically they can be grouped in bunches of 10^{12} to 10^{13} ions or electrons, but enough macroparticles must be in the calculation to create statistically significant results. Arcing and collisional (particle interaction) problems are not handled well by PIC codes. At least two models exist for breakdown: streamer formation and avalanche. PIC codes usually employ the avalanche description since the fields are usually rising rapidly, and streamer formation is negligible. Air breakdown and air chemistry are problems in that their handling is necessary, but techniques or data are not implemented or they are unavailable. The presence of these effects needs to be ascertained, the proper algorithms and data must be determined, and only then can they be added to PIC codes. Other investigations on breakdown are on the leading edge of current knowledge. These are looking into explanations and behavior of surface and volume arcing and breakdown in oil, water, and other insulators. Two general types of unknowns limit the accuracy of PIC codes: electron cross sections, and initial conditions. These quantities are needed to describe the formation of streamers, the effects of photoionization, and insulator and surface breakdown. Initial conditions show up as unknown properties of trace materials in the system; these can include cleaning materials, residual gases, and other contaminants.

C. System Codes

System codes are used to understand and study the relationship between various elements in a high-power system: sources, transmission lines, antennas, propagation effects, etc. These typically start with constraints on a desired system (such as size, weight, power, etc.), and are used to define what components may be used to deliver the required results. Some system codes use a single parameter associated with each system component, and some may use a probability of the component's output. This second type produces a probability for the system performance. Examples of system codes are HEIMDALL [8], MIPPER [9], ARES [10], and DREAM [11].

IV. DEVELOPMENT OF MODELING CAPABILITY

The primary missing component in the capability to model systems lies in modeling electron interaction with other particles, gas breakdown and streamer formation, and the effects of photoionization. For the modeling and analysis of high-power sources, transmission systems, and antennas, the basic requirement in a computer code is a three-dimensional, hybrid PIC code with fluid-dynamic capabilities. A three-dimensional capability is required to model a system with no planar or axial symmetries, and to allow a general solution for the system geometry.

A. Initial Design Codes

After the system concept has been defined, the initial design can be undertaken with linear codes. These will minimize high-field areas of the system, indicate where breakdown may occur, show the general form of the magnetic and electric fields, and suggest how the system design may be altered to improve its performance.

B. Final Analysis Codes

The current capabilities of linear and statistical codes are sufficient for most problems. Development is needed, however, in input data for both the linear and nonlinear codes. If the program requires system responses of any hardware or platform with any degree of hardening (40 dB and above), testing will be required to find the actual frequency-dependent transfer function of the external energy to the interior (or from the inside to the outside). In addition, methods must be found to estimate the properties of cavity interiors. Most likely, a program of testing and analysis can lead to good input methods for statistical code for the effects of apertures and interior

effects. A three-dimensional PIC code with combined PIC and fluid-dynamics capabilities such as LSP [12] is needed to model 1) ionization by beam electrons and secondary electrons, 2) streamer formation, 3) surface breakdown, and 4) photoionization.

C. Model Development Needs

Unfortunately, the research required to develop a three-dimensional PIC code with combined PIC and fluid-dynamics capabilities in general can be extremely broad. An alternative approach is the experimental evaluation of the appropriate quantities to model these empirically. Depending on the empirical algorithms developed for these behaviors, code capabilities such as PIC and fluid-dynamic descriptions may or may not be necessary. Thus, the starting point in modifying existing codes and which codes to modify are not well defined.

In the codes that do combine PIC and fluid-dynamic capabilities, there are three primary developmental issues:

- Rudimentary algorithms or data for electron cross sections may not exist. Depending on the system requirements, a literature search may supply the necessary information.
- The physical mechanisms for streamer formation, volume breakdown, and surface breakdown are not well understood.
- Inclusion of the initiation and subsequent effects of photoionization in the relevant models is incomplete. Empirical relations for photoionization need to be developed and inserted into the codes.

Depending on the system requirements, an understanding of the formation of streamers may not be a necessary capability; if the fields rise rapidly enough, only avalanche may be necessary to explain arcing. Also, the code requirements for the addition of these properties are affected to a certain extent by the initial design of the system; it may not require capabilities in all these areas for an adequate simulation.

V. CONCLUSIONS

The codes with good potential to include all of the necessary features are LSP and MAGIC [13]. However, enough unknowns in the system design and required physics exist so that additions may be made to codes such as QUICKSILVER [14] or ICEPIC [15] for an equally correct response prediction.

Another design or system feature that may be important is the cleanliness of the system. Contaminants may lead to breakdown at unexpectedly low field levels. For an adequate description of this, the materials present and how their presence alters the physics of the system must be known or experimentation must be undertaken to empirically evaluate these effects.

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